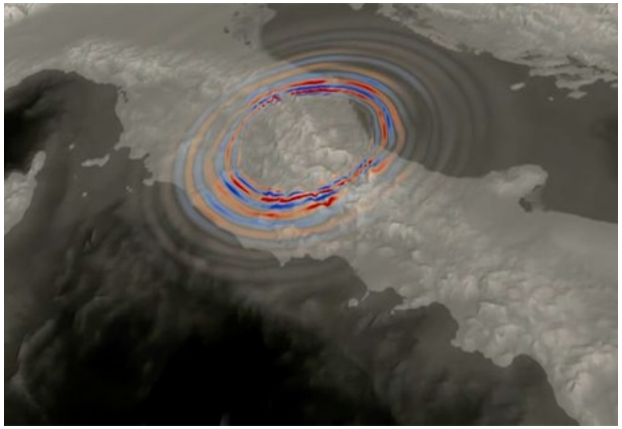


Deterministic 3D Ground Motion Simulations of the Central Italy Earthquakes

Aybige Akinci[1], Arben Pitarka[2], Pietro Artale Harris[1], Mauro Buttinelli[1], and Pasquale De Gori[1]

[1] Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy

[2] Lawrence Livermore National Laboratory, Livermore, U.S.A.

ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA

INGV SECURE REGIONAL-SCALE EARTHQUAKE GROUND MOTION PREDICTIONS THROUGH PHYSICS-BASED AND EMPIRICAL APPROACHES: A CASE STUDY CENTRAL ITALY

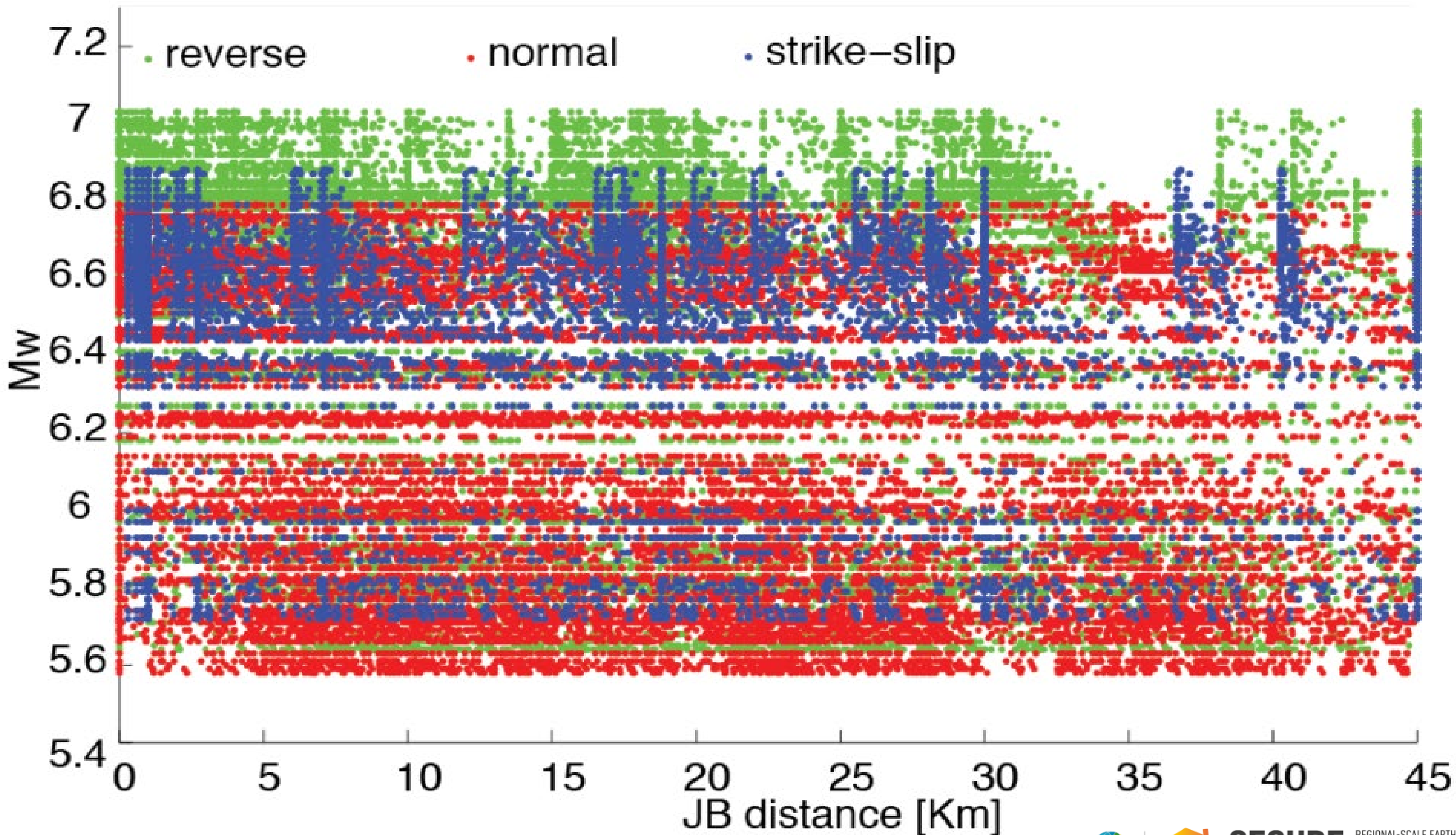
Lawrence Livermore National Laboratory

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC.

zionale di Geofisica e Vulcanologia

Motivation1:

Can we develop a database of synthetic earthquakes to fill the gaps of lack of data?

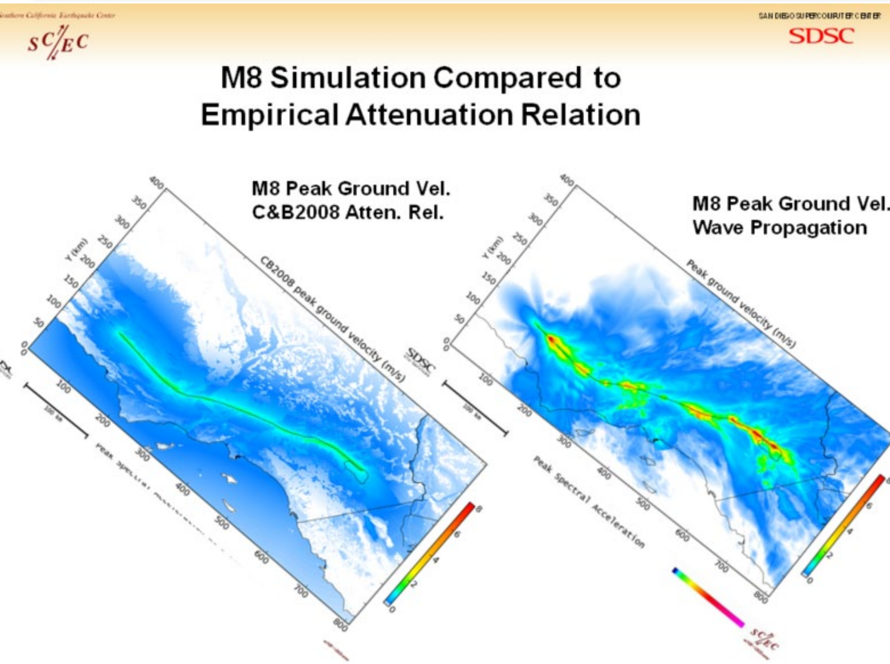


:
a
to:
r of

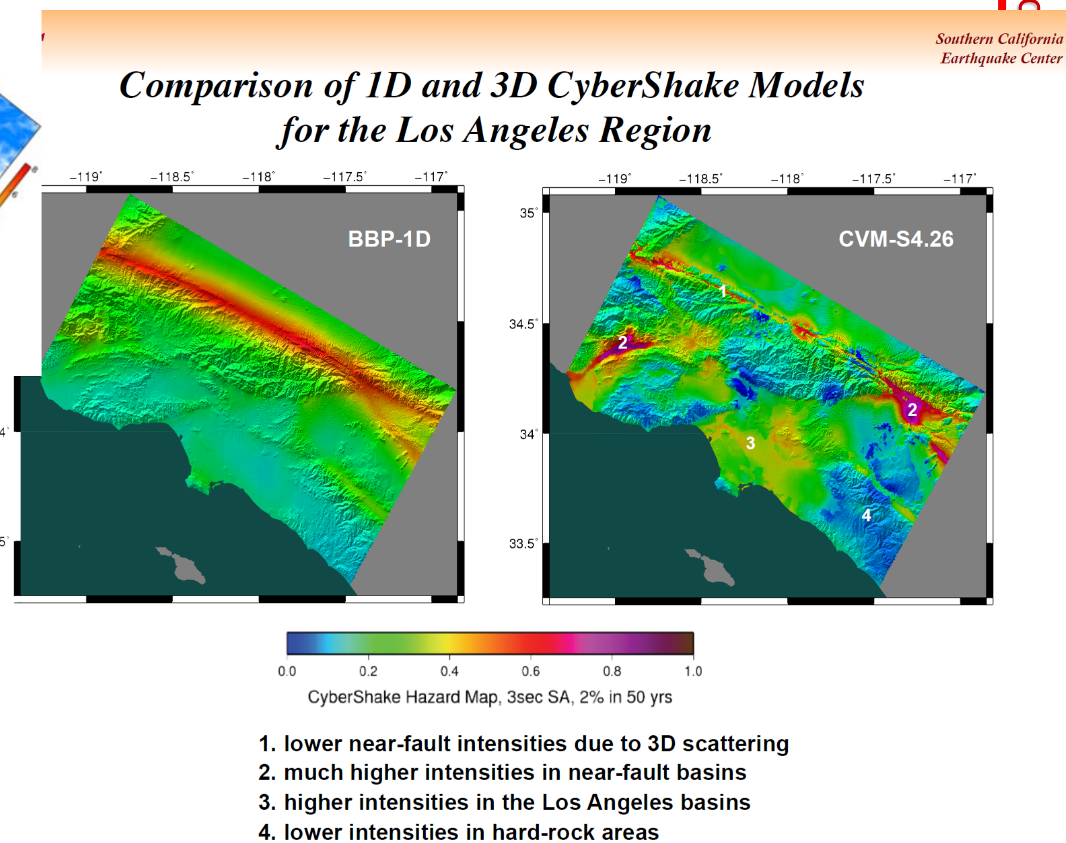
Istituto Nazionale di Geofisica e Vulcanologia

INGV SECURE REGIONAL-SCALE EARTHQUAKE GROUND MOTION PREDICTIONS THROUGH PYHSICS-BASED AND EMPIRICAL APPROACHES: A CASE STUDY CENTRAL ITALY

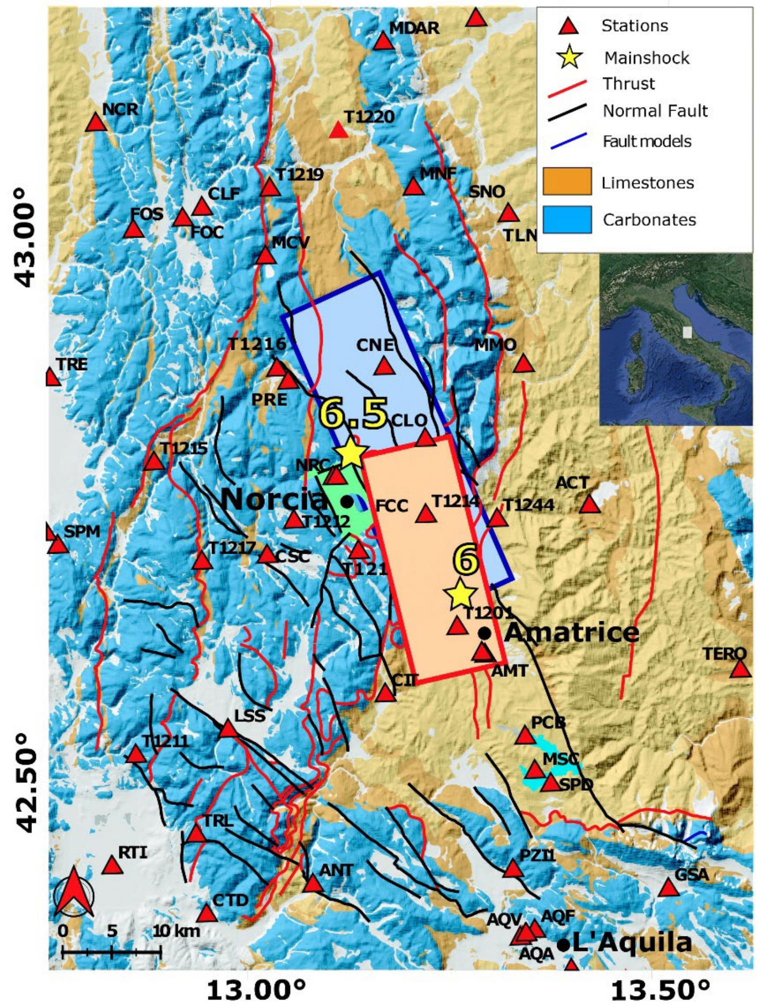
Motivation2:



Physics-Based Simulations for Seismic Hazard Anaylsis (CyberShake Project)



GMPEs do not capture certain well-known factors influencing ground motion characteristics, especially those associated with fault rupture processes**, complex source-site** propagation of seismic waves, and sedimentary **basin** response, particularly in the **near-fault** region.



Motivation3:

- The central Italy sequence started with the **M_w6.2 Amatrice earthquake** on August 24, 2016.
- The **Norcia earthquake**, occurred two months later, was the largest event **M_w6.5** in the sequence.
- Recently, a magnitude **Mw6.3 L'Aquila** earthquake struck the region in 2009, located 50 kilometers south of the Amatrice earthquake.
- The 2016 Norcia earthquake was one of the **best-recorded** earthquakes in Italy.

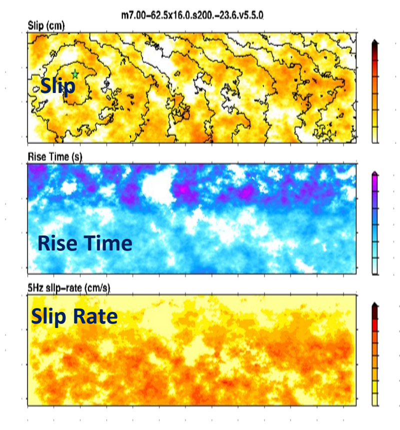
Objectives:

- Investigate **ground motion characteristics** through the synthetic waveforms using fully deterministic approach in 3D up to higher frequencies in the Central Apennines.
- Test an end-to-end **modeling capability** for strong ground motion simulations using registered and empirical data.
- Design a powerful to compute strong ground motions up to higher frequencies which can be used in **seismic hazard estimation and for engineering applications**.

Physics-Based Ground Motion Simulation Method

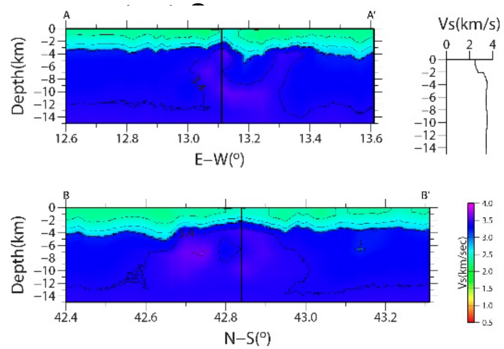
Deterministic Approach

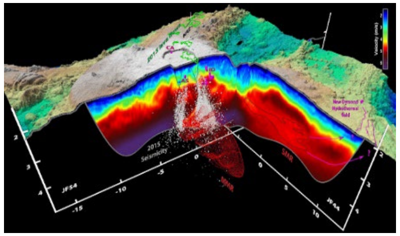
Kinematic Rupture Model



Wave Propagation

3D Linear anelastic,





GP Method

Kinematic rupture models generated using a technique developed by Graves& Pitarka, 2016).

It incorporates small stochastic rupture variability, and deterministic large slip areas and depth dependent rupture velocity and slip rate.

Un modello di velocità locale 3D ben vincolato che incorpora un dettagliato modello tomografico della crosta (Chiarabba et al., 2018).

SW4 Code

A time domain 4th order finite difference code developed at LLNL (Peterson & Sjogreen, 2018).

It uses near surface curvilinear mesh design to model surface topography with high numerical accuracy.

Computational Requirements

Simulations are performed using a physics based deterministic approach, modeling the earthquake rupture and elastic wave propagation and running the parallelized CPU version of the SW4 code

LLNL QUARTZ Supercomputer
NORCIA M6.5 EARTHQUAKE
Model Dim. covers : 102kmx88kmx31km
Min grid spacing : 25 m (grid point 3X10^9)
Min Vs : 600m/s
F_{max}: 5Hz
Ground motion duration : 40 s
With topography
CPUs : 10800, Wall time : 21 hrs (largest run-topo)
Without topography
CPUs : 3600, Wall time : 4.5 hrs (run with no topo)

INGV SECURE REGIONAL-SCALE EARTHQUAKE GROUND MOTION PREDICTIONS THROUGH PHYSICS-BASED AND EMPIRICAL APPROACHES: A CASE STUDY CENTRAL ITALY

Istituto Nazionale di Geofisica e Vulcanologia

Physics Based Earthquake Rupture Models Produced with the GP Method

Earthquake M_o , Faulting Type , Fault Length and Width

Slip Distribution

Spatially random slip distribution Von Karman Power Spectrum
-deterministic for low-wavenumbers
-stochastic for high-wavenumber squared fall-off
-magnitude dependent correlation lengths

Rupture Speed Vr

-depth dependent specified to average 75%–80%Vs

Rupture time

-scaled with cubic root of magnitude (Graves and Pitarka, 2016)
-local random perturbations that follow normal distribution and partially correlated with the underlying slip distribution

Slip Rate Function

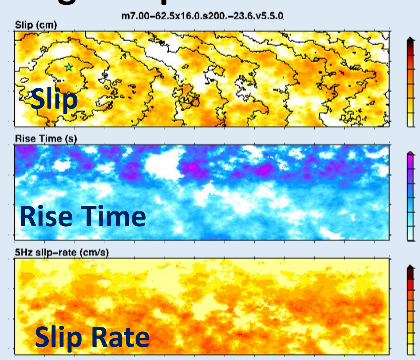
-depth dependent slip rate function shape
-bell-shaped at shallow depth, above weak zone
-transition to Liu-type below weak zone

Rise Time Distribution

-average *rise time scales with $Mo^{1/3}$ (Somerville et al., 1999)*
-partially correlated with with square root of slip
-local perturbations partially correlated with the underlying slip and faulting mechanism
-depth dependent, longer at z<5km

Graves and Pitarka, 2016

Single Rupture Scenario



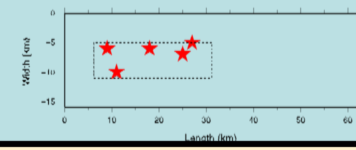
good rule of thumb for a 4th order FDM fmax is based on the requirement that there should be at least 7 grid points per wavelength in the entire domain.

Fmax = Vsmin/7/dx. = 800/7/25=4.6 Hz
Fmax=400/7/25=2.3Hz

Multiple Rupture Scenarios

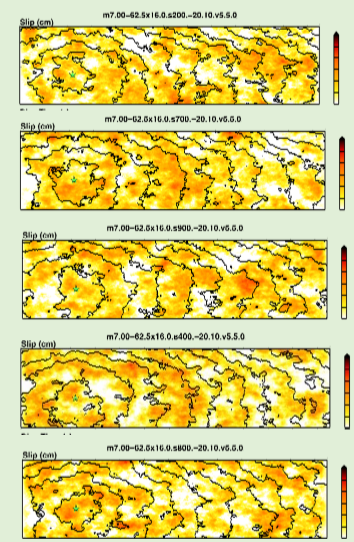
5 Randomized Hypocenter Locations

Location along strike direction : 10% - 50% Fault Length
Location along dip direction: 5-11 km



5 Slip Distributions for a Each Hypocenter Location

S 1
S 2
S 3
S 4
S 5



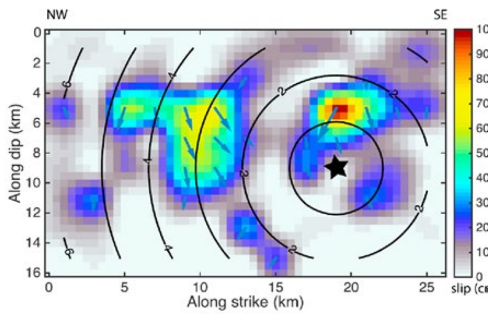
Istituto Nazionale di Geofisica e Vulcanologia

INGV
SECURE
REGIONAL-SCALE EARTHQUAKE GROUND MOTION PREDICTIONS THROUGH PHYSICS-BASED AND EMPIRICAL APPROACHES: A CASE STUDY CENTRAL ITALY

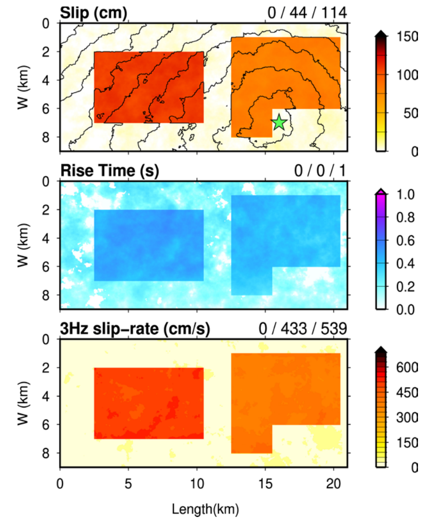
Inverted Kinematic Slip Model

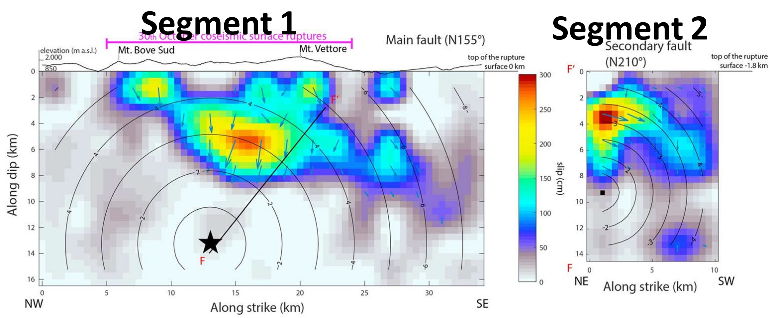
(Scognamiglio et al., 2018, Tinti et al., 2016)

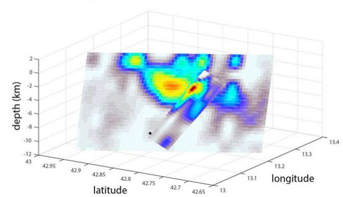
Generated GP16 HR Models



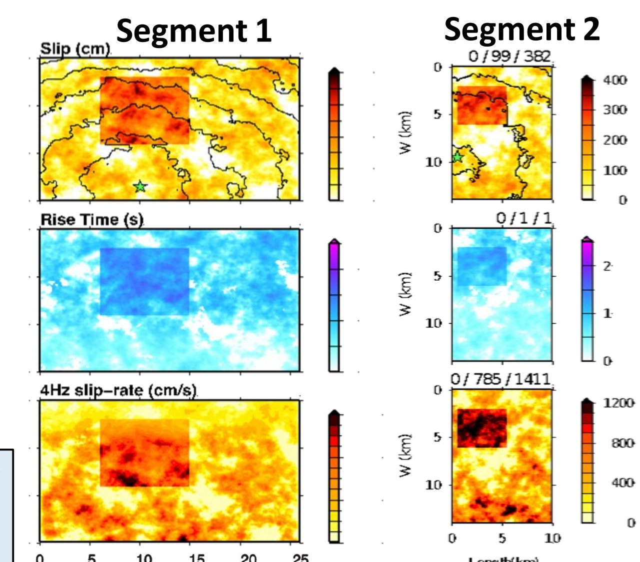
Amatrice earthquake M6.2







Norcia earthquake M6.5



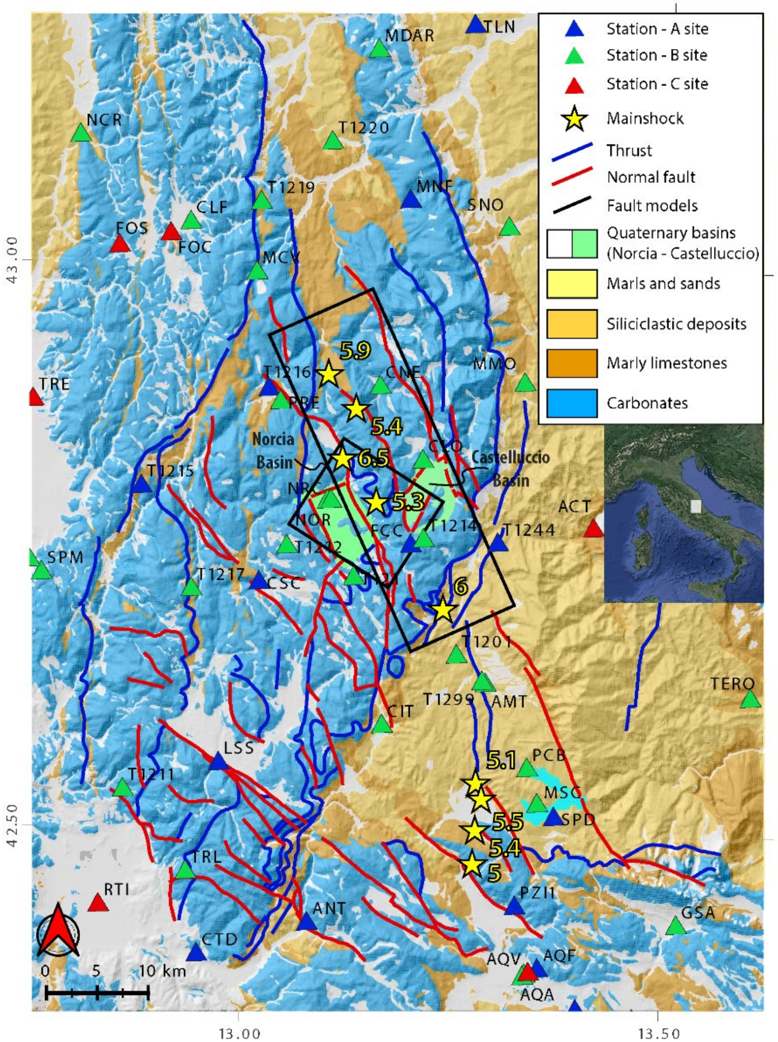
- The slip distribution, peak slip rate, rise time, and rupture time contours computed following the GP16 method where the rupture process is randomly heterogeneous at different scale lengths.
- The slip rise time and rupture velocity are depth dependent. The longer rise time at shallow depths and shorter rise time at larger depths affect the long period and short period contents of rupture generated seismic energy.

Pitarka et al., 2021, BSSA
Akinci et al., 2023, Submitted to BSSA

Istituto Nazionale di Geofisica e Vulcanologia

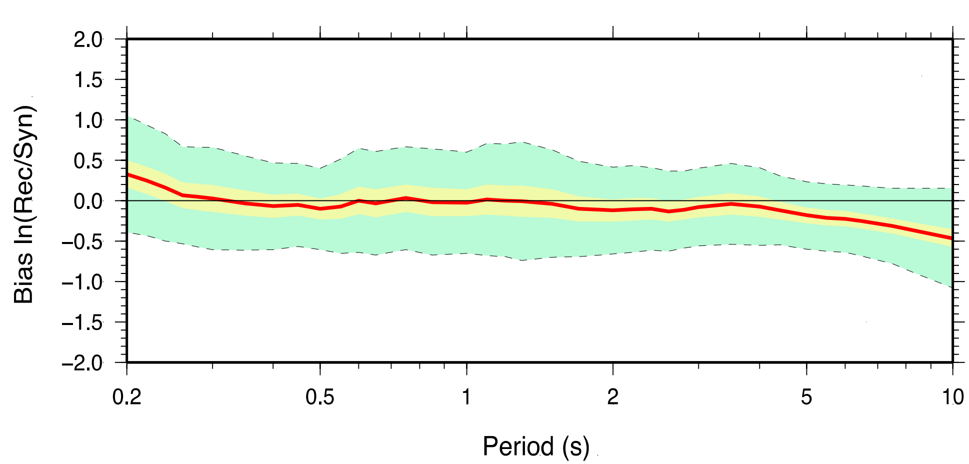
Simulated Ground Motions & Validations: Norcia M6.5 earthquake

Comparison with Recorded Time Histories & Spectral Accelerations



On average our simulations predict the recorded data very well on the entire period range 0.25 to 7 seconds.

Spectral Acceleration Goodness-of-fit



- Evaluating quantitatively the performance of our simulations and the predictive capability of our method.
- Calculating residuals between the recorded and simulated spectral acceleration values, GOF to show how well the simulation fits a set of observations at 41 and 37 stations.

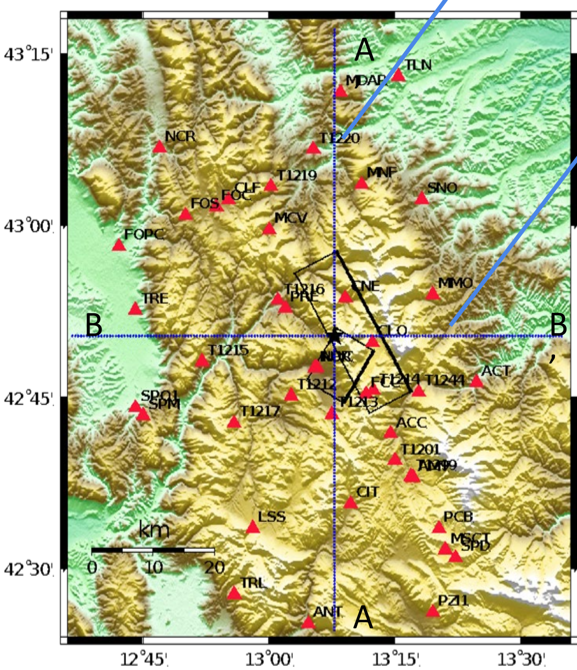
Pitarka et al., 2021, BSSA

INGV

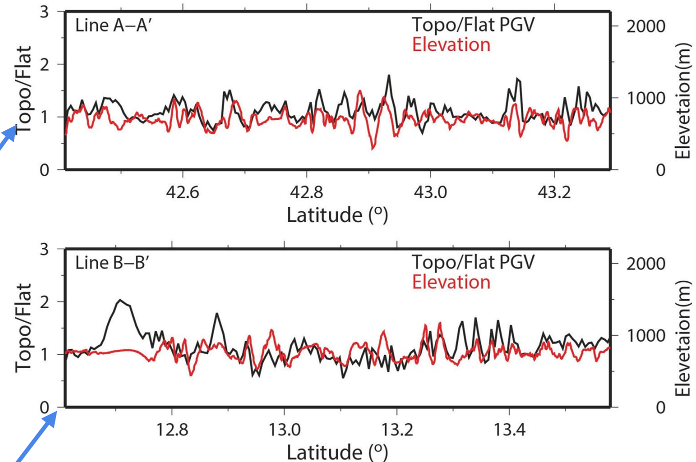
SECURE REGIONAL-SCALE EARTHQUAKE GROUND MOTION PREDICTIONS THROUGH PHYSICS-BASED AND EMPIRICAL APPROACHES: A CASE STUDY CENTRAL ITALY

Istituto Nazionale di Geofisica e Vulcanologia

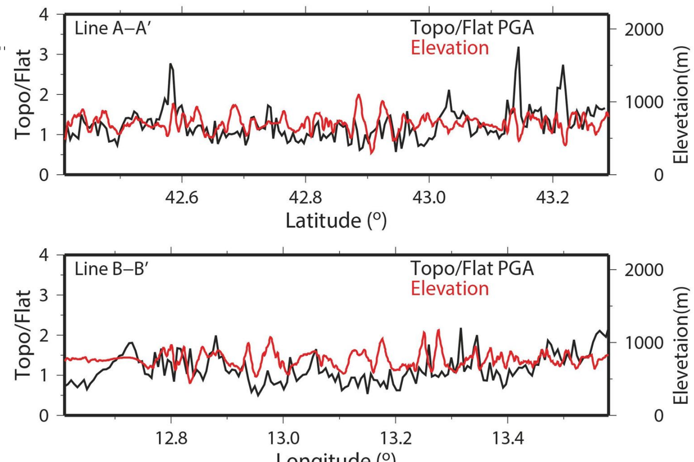
Topographic Effects: PGV correlated with topography (Topo/flat)



PGV

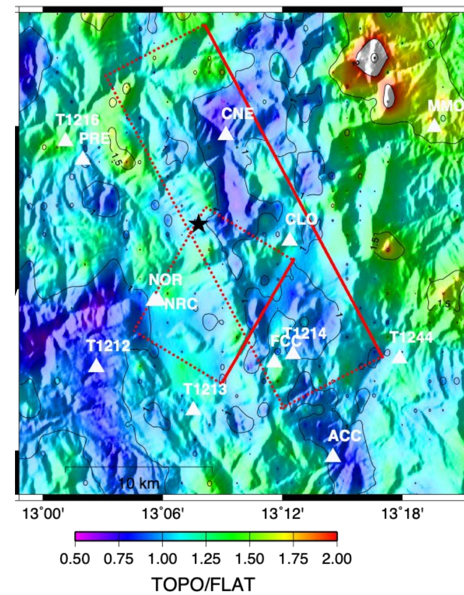


PGA



high-pass filtered at elevation variations lengths of 10 km

3D+Topo/3D Flat



Strong correlation between the spatial variation of PGV and ground surface elevation with PGV being higher at the top of the mountains or hills.

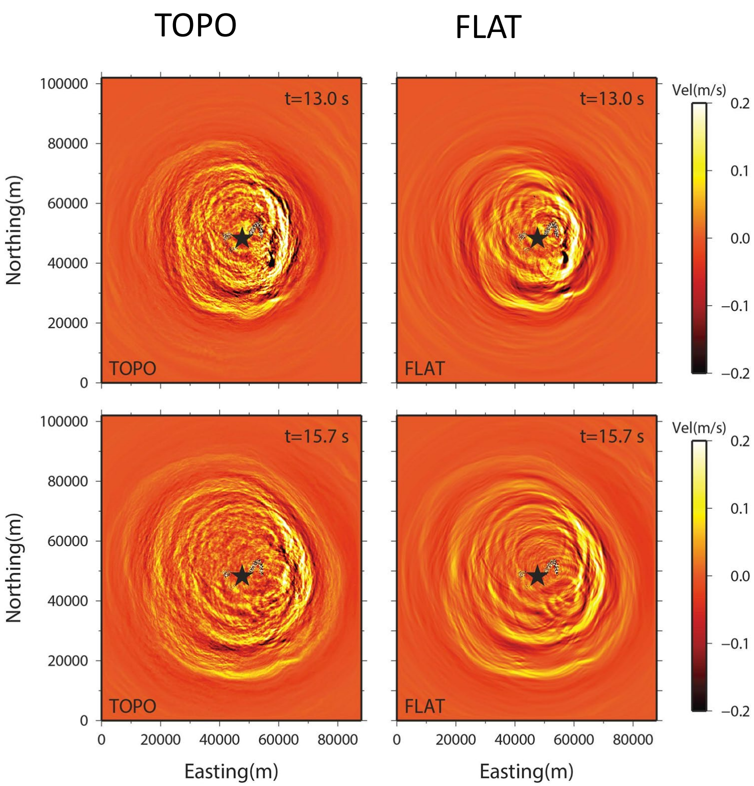
No or very little correlation between the PGA and topography at 0-5 Hz frequency range, complex free surface interaction between high frequency converted waves and the local variations of the topography.

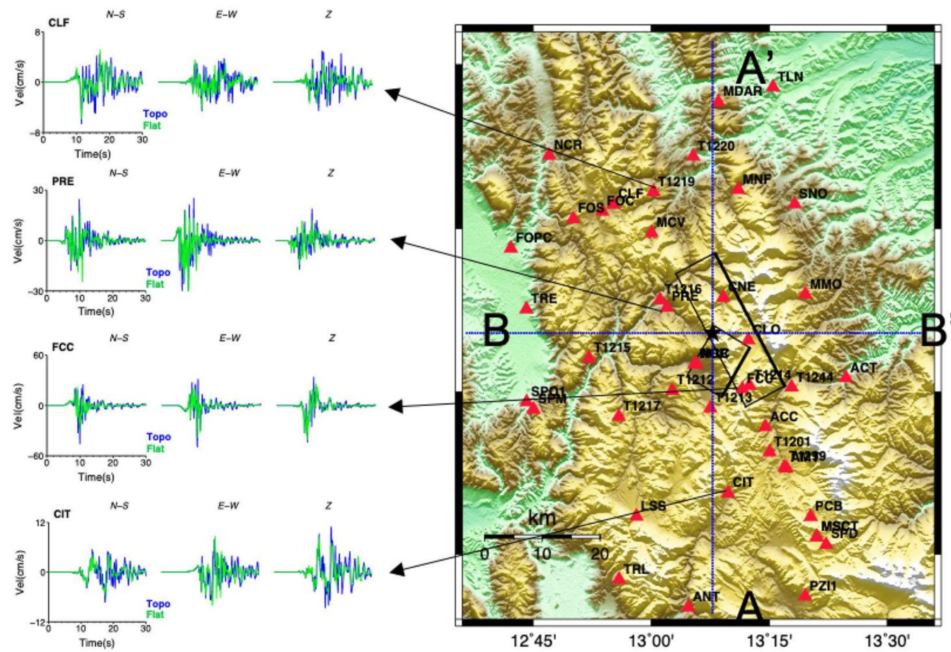
The PGV ratio < 1 shows deamplifications in most of the valleys and amplifications with various strength of up to 2.5 on mountain tops.

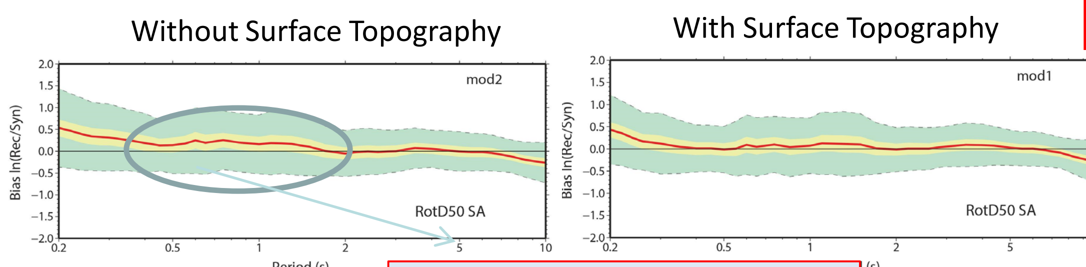
Pitarka et al., 2021, BSSA

Istituto Nazionale di Geofisica e Vulcanologia

Norcia Earthquake: Effect of Topography on Ground Motion Velocity Time Histories (0-5Hz)







~30% reduction in ground motion amplitude for periods < 1 .5 seconds

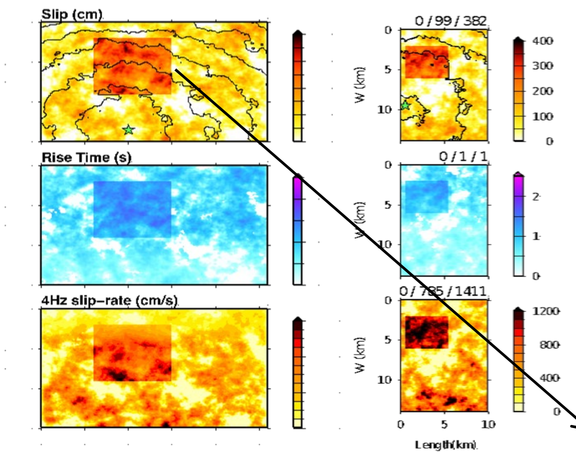
Pitarka, A., **Akinci, A.,** De Gori, P., Buttinelli, M., 2021. Deterministic 3D Ground-Motion Simulations (0–5 Hz) and Surface Topography Effects of the 30 October 2016 Mw 6.5 Norcia, Italy, Earthquake. Bull. Seismol. Soc. Am. 112 (1), 262–286, doil: 10.1785/0120210133.

Synthetic seismograms calculated TOPO model show larger amplifications and more coda and relatively longer duration with respect to those by the FLAT topo model.

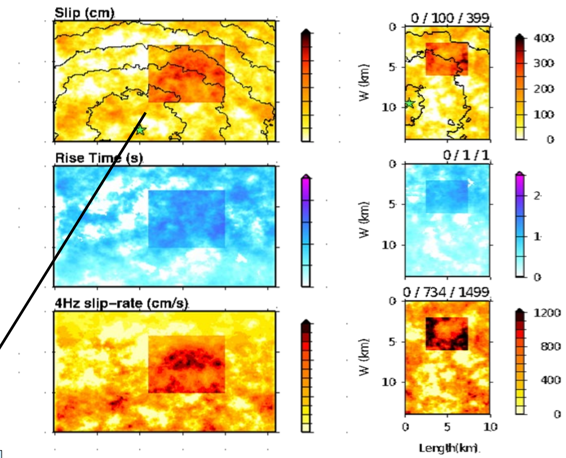
Istituto Nazionale di Geofisica e Vulcanologia

Norcia M6.5 Earthquake: Sensitivity of Ground Motion Amplification Pattern to Slip Distribution

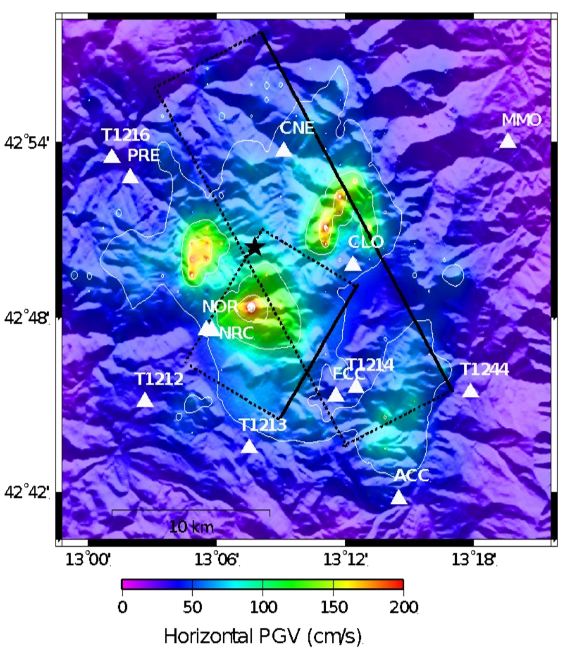
Proposed Rupture Model



New Rupture Scenario Model

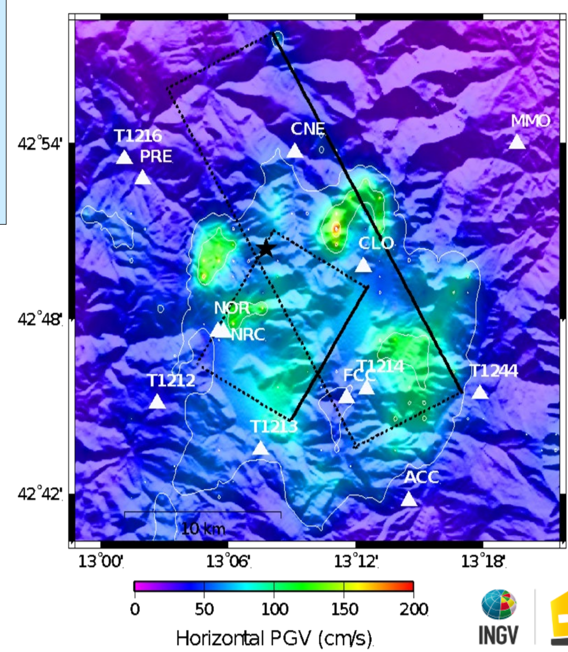


PGV Map



Note that the two rupture models have different location of large slip patches.

PGV Map



- Location of high PGV areas correlates with areas of large slip patches.
- It is clear that the ground motion amplification pattern depends on the relative location of the large slip patches.
- These PGV plots suggest that for a normal faulting earthquake the ground-motion variability is expected to be high in regions over the hanging wall of the fault.

Pitarka et al., 2021, BSSA

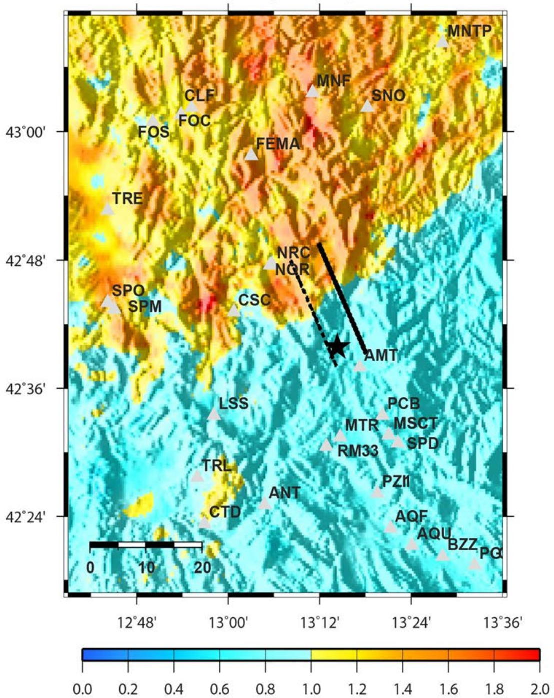
INGV

SECURE REGIONAL-SCALE EARTHQUAKE GROUND MOTION PREDICTIONS THROUGH PHYSICS-BASED AND EMPIRICAL APPROACHES: A CASE STUDY CENTRAL ITALY

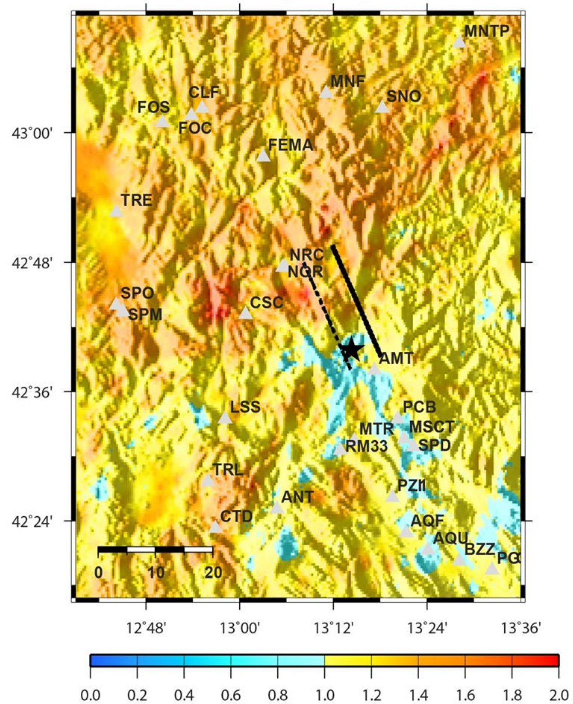
Istituto Nazionale di Geofisica e Vulcanologia

Amatrice M6.2 earthquake: PGV Ratio Maps Rup5/Rup5.1, Rup5/Rup6: Rupture Complexity and Directivity Effect

PGV Rup5/Rup51



PGV Rup5/Rup6

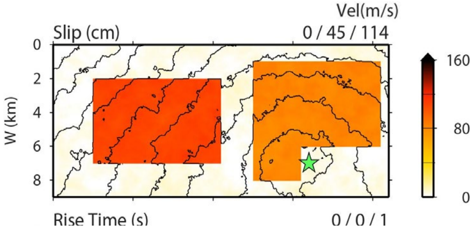


- **Rup5/Rup5.1**

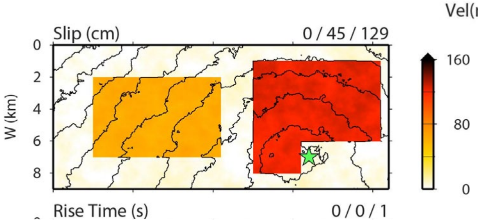
Mod5 produces stronger ground motion and stronger directivity effects toward the north in agreement with the observed data

- **Rup5/Rup6**

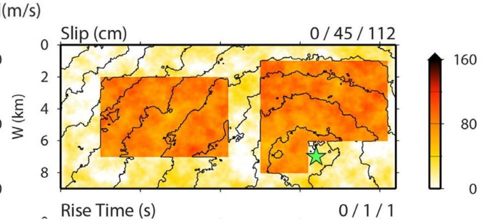
overall, **Mod5** produces stronger ground motion, especially to the north, since it produces stronger directivity effects respect to Mod6 which is a smoother version of model 5, more stochastic variability and less deterministic features compared to Mod5.



Rupture Scenario Model5.0 (Rup5)



Rupture Scenario Model5.1 (Rup51)



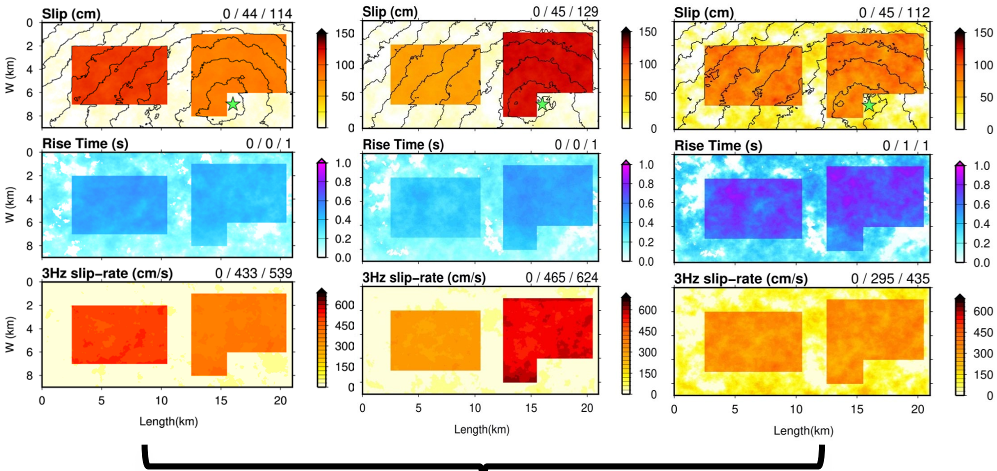
Rupture Scenario Model6.0 (Rup6)

Akinci et al., 2023, submitted to BSSA

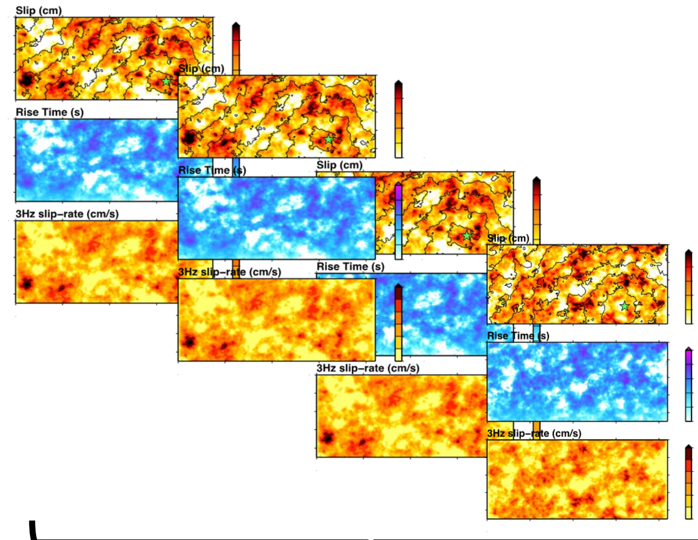
Vulcanologia

INGV SECURE REGIONAL-SCALE EARTHQUAKE GROUND MOTION PREDICTIONS THROUGH PHYSICS-BASED AND EMPIRICAL APPROACHES: A CASE STUDY CENTRAL ITALY

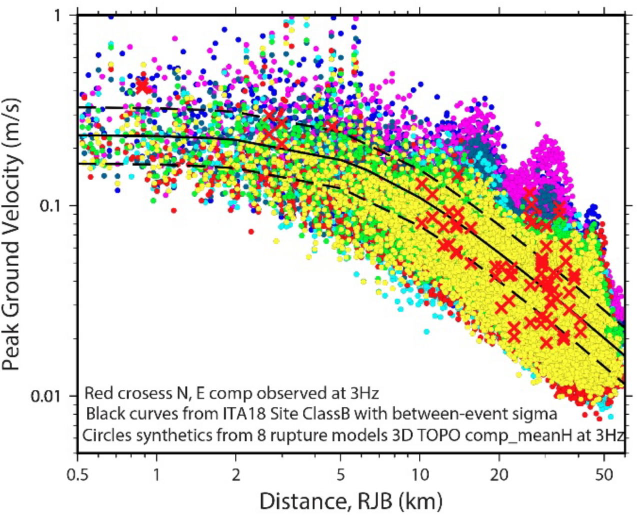
Amatrice M6.2 earthquake: Sensitivity of Ground Motion Amplification Pattern to Slip Distribution, GMMs and sigma

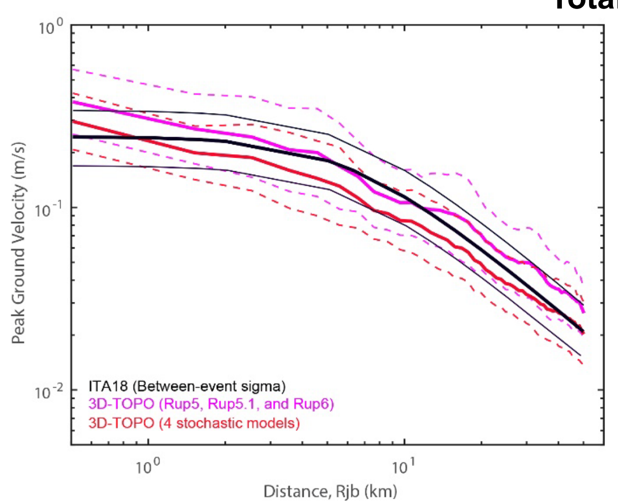


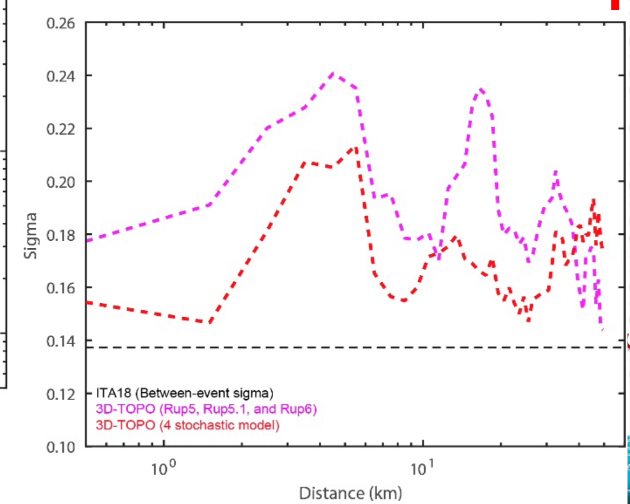
Hybrid Rupture Models



Totally Stochastic Rupture Models







INGV

SECURE REGIONAL-SCALE EARTHQUAKE GROUND MOTION PREDICTIONS THROUGH PHYSICS-BASED AND EMPIRICAL APPROACHES: A CASE STUDY CENTRAL ITALY

Akinci et al., 2023, Submitted to BSSA

Istituto Nazionale di Geofisica e Vulcanologia

Thank you for your attention!